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NO. 389

PRELIMINARY RESULTS ON THE PHYSICAL PROPERTIES OF AQUEOUS FOAMS AND THEIR BLAST ATTENUATING CHARACTERISTICS

by

F.H. Winfield and D.A. Hill

PROJECT NO. 97-80-01

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ABSTRACT

Preliminary results are presented from experiments designed to correlate the physical properties of aqueous foams with their blast attenuation characteristics. Using commercial concentrates for detergent based (high expansion) foams, the physical properties of density ($\sim$ .4 ± .2 lb./ft^3), subsidence rate ($\sim$ 2-5 ft./hr.), drainage time (10-25 min.), ball penetration rate (1-4 ft./min.) and shearing torque (10-25 in.-oz.) were measured. The shock front in foam showed a decrease in the damage-producing properties of peak overpressure (reduced X20) and positive impulse (reduced X4). An increase was recorded in shock front time of arrival (X2-3), rise time ($\sim$ 1 ms. vs 1 μs.) and positive duration (X3). The project was terminated before the correlation between physical and blast attenuation properties could be studied.

(U)

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1. INTRODUCTION

It is well known that the peak overpressure in the shock wave from a small explosion, and therefore its effect on other media, is attenuated by the use of aqueous foams. Attenuation factors of up to 10 have been recorded.

The foams used initially are generated from commercial fire-fighting foam concentrates. As these are designed for putting out fires cheaply and efficiently, and not for attenuating explosions, the foam characteristics for the latter job are likely not optimum.

The purpose of this study is to measure the physical properties of the foams as well as their blast reducing characteristics and, by comparing the two, to develop a better understanding of the attenuation process and to create more effective foams for this application.

There are three current problems in applying the foams to an explosion: The water drains through the pile of foam to the bottom so that the foam subsides in 20 min.; the high-expansion foams cannot be piled more than 2 ft. high without support (only 2 in. high for the low-expansion foam); finally, at sub-zero temperatures the foam freezes and is of no use. The sort of physical variables which are likely to be important include the foam density, bubble diameter distribution, foam surface tension and stiffness or

shear strength or "viscosity". Some of these variables may be under partial control through the chemical composition of the foam concentrate, while others are under control through physical variables, such as foam nozzle selection, water pressure, temperature and flow rate, % concentrate/water mixture and ambient air temperature and humidity.

Of course, it is not possible to control each physical parameter describing the foam separately as they are related by the equation of state of the foam.

As this project was terminated before completion, some of the preliminary results achieved to date will be reported. Unfortunately, the limited number of results does not allow the correlation of blast attenuation characteristics with the physical properties of the foams.

2. FOAM GENERATION

Commercially-available fire-fighting foam systems create foam by mixing a concentrate with water in some manner and delivering the foam through a suitable hose and nozzle to the fire. The main types of foams are: detergent-based (high expansion), protein-based (low expansion), AFFF (aqueous film-forming foam), "light-water foam", and specialized foams. One source of the latter in Canada is Laurentian Concentrates Ltd. of Ottawa, who have made a specialized agricultural foam as well as water-gel foams and other varieties. The protein-based foam concentrates are pre-mixed for use in a 3% or 6% standard solution with water. The detergent-based foams can be mixed in a solution of variable concentration from 1% to 6%. The 6% concentration provides a stiffer foam of the same density as the 1% concentration.

The foam expansion ratio is defined as the ratio of the expanded foam volume to the volume of water and concentrate used. The protein-based foams have expansion ratios of approximately 10-100 while the detergent-based foams can be created with ratios from ∿ 50-500. Our detergent-based foams were used expanded X100 or X200 so the foam density was .3-.6 lb./ft^3 compared to 62.4 lb./ft.^{3} for water. The only low-expansion protein-based foam used was

"Chieftain 6% protein" concentrate.* It gave a foam smelling like rotten potatoes and generally subsiding more rapidly than the detergent foams. Three commercially-available high-expansion detergent-based foams were used: Chieftain XHX brand, Rockwood high-expansion Jet-X concentrate** and "Lorcon Fullex".***

The foam is generated as follows: Water is pumped from a 1000-gal. tank through a Hale gasoline-powered water pump and delivered into a Rockwood in-line eductor. The eductor is a straight length of metal pipe of constricted centre diameter which creates reduced pressure and draws foam concentrate through a side tube from a 5-gal. can. An adjustment on the eductor allows continuous control of the water-concentrate mixture from 1% to 6%.

The water/concentrate mixture then flows through 150 ft. of 1-1/2" I.D. (2.1" O.D.) fire hose to a "Rockwood super Jet-X nozzle" which creates the foam. The "nozzle" actually consists of a regular water spray nozzle leading into a 1' diameter, 3' long metal horn with a conical cloth mesh at the end of it which creates the foam. A photo of the foam generation process is included in figure 11 (b). To produce a more consistent foam for the experiments it was found better to let the foam generator run 1 minute before loading foam into the equipment. A volume of 4' x 4' x 8' (128 ft.^{3}) is normally filled with foam in 1/2 min. The foam temperature is normally a few degrees Celsius warmer than the original air and water temperatures since the water is heated as it goes through the water pump.

On a windy day, foam generated upwind is partially broken as it forms, creating a wetter, more dense foam.

* available from Safety Supply Company,
214 King Street, Toronto, Ontario.

** available from G.W. Rockwood Company, 80 Second Street,
S. Portland, Maine 04106

*** available from Laurentian Concentrates Ltd.,
1785 Woodward Drive, Ottawa, Ontario.

3. CHARACTERIZATION OF FOAM PHYSICAL PROPERTIES

To measure the foam density, subsidence and water drainage as a function of time, a small test box of dimensions 1' x 1' x 1' was constructed of transparent lucite and set up on a weighing scale. The water drained from the foam was collected in a beaker and measured with time. The time for 90% of drainage to occur was recorded as well as total volume of water collected when the foam was gone. By recording the height and weight of foam (drained water not included) vs time, the foam subsidence (loss of height) and density vs time were measured.

Data from these tests are recorded in table 1 and the most informative results are plotted on the graphs of figures 3 to 10.

The majority of measurements were performed in a large test box, a 4' x 4' x 8' structure set up to record the penetration rate of a falling ball. The initial shear strength of the foam was tested at heights of 2', 4' and 6' by rotatable paddle wheels. The subsidence of the foam was measured through the front window and recorded. The foam temperature was also measured at the 4' height in the box. Finally, the foam was photographed vs time at the 2', 4' and 6' marks as shown in figures 1 and 2. Figure 1 shows the foam at 4' height just after creation. A circular target area is drawn in for further close-up photos and scales are marked on in inches. The lower half of the photo shows the advantage of putting a black plate behind the foam. The plate is 3" behind the glass, as a depth of 1-1/4" was shown to interfere with the foam structure as the foam subsides. The close-up in figure 2 allows closer examination of the foam structure as well as the measurement of the bubble diameter distribution at the glass plate. Details of the above measurement procedures are found below.

The only other measurements done were the viscosity and surface tension of water/concentrate mixtures over the range from pure water to pure concentrate. Viscosities were determined by the capillary (Fisher-Ostwald) viscometer, and surface tension by the ring method (Cenco-du Nouy tensiometer). The concentrate was Jet-X high-expansion foam concentrate, of density 0.967 gm./ml. The results of these measurements are shown in Table 2. The data in the table confirm the expectations that the mixture

viscosity shows a simple linear variation between the values of the two liquids, but that the surface tension is lowered in a very dramatic way by the addition of small amounts of detergent concentrate.

3. (a) Density, Subsidence and Drainage Data

Since the time dependence of the density, the foam height and the water drainage are obviously related, they are discussed together. All original data characterizing the foams are contained in table 1. The time dependence of foam density is shown in figure 3. The spread in the measurements on the same foam, Jet-X, is unusually large but serves to illustrate the problems of reproducibility. The flat portion of each curve is where most of the water has already drained through the foam (90% drainage times of 10-20 min. are found in table 1) and the relatively dry foam retains constant density as it continues to subside. The foam density depends on water temperature, as seen in figure 4, where the initial density and the value after 10 min. are plotted.

As can be seen from the statistics for foam density in table 1, the scatter in measured density values is less initially than after 5 or 10 minutes. The scatter at the 10 min. mark is reduced by using the density scaled to zero time. Absolute density values are ± 15%.

Typical data for the subsidence in foam height in the large box are given in figure 5. The average subsidence rate in ft./hr. is noted on the legend and tabulated in table 1. The average subsidence rate in the 1 ft. box is 2-3 times slower than for the 8 ft. box. The subsidence rate expressed as a percentage of the original height is faster for the 1 ft. box. Therefore, the subsidence rate as a function of foam height does not fit a simple theory.

The drainage of water was characterized in two ways: by the total volume of water drained and by a time characterizing near completion of drainage. As the process was so rapid it was found simplest to use the time for 90% completion as the characteristic time.

To demonstrate that the subsidence process depends partly on the drainage process, the drainage time has been plotted vs subsidence rate (figure 6) indicating a generally longer drainage time for a slower subsidence rate. Finally, the total water drainage in 1 cu. ft. plotted vs initial density (not shown) gives a good straight line through the origin as these are just two methods of measuring the same thing, namely, the weight of water initially in 1 cu. ft. of foam.

3. (b) Penetration Rate and Shear Strength

One test of foam strength is a ball penetration rate measurement. A 3.9" diameter 26g foam polystyrene ball (density 2.4 lb./ft.^{3}) falls from a height of 8' through the foam, partly counterbalanced by a 6g ball rising in air outside the box. The ball depth is plotted against time, as illustrated in figure 7. The average penetration rate from 2 ft. to 7 ft. is calculated and recorded in table 1. Taking into account the 6g counterweight and the 5g kinetic friction of the pulley system, the net effective ball weight is 15g. This measurement was performed at 5 min. after foam generation. The penetrating ball usually leaves a hole in the foam, which does not close over. Therefore, this experiment measures the penetration strength of a quasi-solid and not the "viscosity" of a quasi-fluid.

A second test of foam stiffness is to measure the shear strength. One rotating paddle apparatus was set up at each of the 2', 4' and 6' high positions. Each apparatus consists of four vanes 18" long and 8" wide attached every 90° around an aluminum rod to form a paddle wheel. The rod leaves the chamber through a well-greased bearing mount and terminates with a fitting for a torque gauge.* Each paddle is started in the same position and rotated in the same direction so that the residual torque due to friction alone is reproducible at 20 ± 2 in.-oz. The foam adds another 10-25 in.-oz. of torque. This measurement is done as the torque required to just start rotation of the vanes. Once rotation starts a path has been broken for the vanes through the foam and the residual torque due to the foam is only a few in.-oz. and hard to measure. Less shearing torque is required higher up in the foam, as seen in figure 8. In fact, all foam properties can be expected

* "Torque Watch", model F6500C-3, Waters Manuf. Inc., Wayland, Mass.

to depend on height because the water drains down through the pile of foam to the bottom and because the top foam tends to crush the foam below.

Finally, the idea that ball penetration rate and shear strength are two measures of the foam stiffness is confirmed by the data plotted in figure 9. Both measurements involve the force required to break a path through the foam.

3. (c) Other Results

To some extent the foam stiffness should be related to both subsidence and penetrability. That this is the case is seen in figure 10. The subsidence rate as measured in either the large or small container is related to the ball penetration rate. In fact, the net subsidence rate (8' rate-1' rate) shows even better correlation (unpublished).

From the data in table 2 other graphs were plotted. No variable was found to depend strongly on relative humidity. There may possibly be a decrease in subsidence rate as relative humidity increases from 30% to 75%, but it is not statistically significant. Plots of data vs foam temperature rather than water temperature show no improvement. Various plots relating shear strength to ball penetration rate, including scaling for density, showed no relationship.

The major conclusion from the measurements of physical properties is that a more reproducible, longer-lasting foam is required, which could likely be produced by experimenting with further chemical stabilization of the foam. One might also investigate why the subsidence rate varies with height.

4. EXPERIMENTS USING EXPLOSIVE CHARGES

4. (a) Layout of Experiment

The arrangement of explosive charge, pressure and temperature gauges, and foam-containing fence is shown in figures 11A and 11B. Calibration and proofing experiments leading up to this configuration are described in section 4 (c).

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TABLE NO. 1

CHARACTERIZATION OF FOAM PHYSICAL PROPERTIES:

DENSITY, SUBSIDENCE, DRAINAGE, SHEAR STRENGTH AND PENETRATION RATE

Test No.	T Air (°C)	T Water (°C)	T Foam (°C)	Relative Humidity ± 5%	Density, ρ(t), (lb./ft.^{3}) t in min.					Subsidence (ft./hr.)		Drainage		Initial Shear Str. (in.-oz.)			Ball Penetration Rate (ft/min.)
					ρ(0)	ρ(5)	ρ(10)	ρ(30)	$\frac{\rho(0)}{\rho(10)}$	in 1 ft.	in 8 ft.	t for 90% (min.)	Vol. (100%) (ml.)	at 2 ft.	at 4 ft.	at 6 ft.	
Jet-X																	
3	24	21.5	26	62	.90	.26	.31	.80	2.9	2.4	6.5	7	350	19	14	5	5.1
4	20	19.5	-	53	.76	-	.24	.21	3.1	1.1	-	24	350	-	-	-	-
5	20	19.5	-	44	.82	-	.17	.90	4.8	1.5	-	10	345	-	-	-	-
6	21	20	-	37	.82	-	.20	.18	4.1	1.3	-	10	310	-	-	-	-
7	24	21.5	-	30	.91	.23	.16	.8	5.7	2.2	-	13	350	-	-	-	-
8	20	20	-	60	.6	.28	.14	.14	4.3	.8	-	12	290	-	-	-	-
9	20	20	-	56	.9	.20	.20	.16	4.5	1.0	-	8	360	-	-	-	-
10	20	18	26	65	1.3	1.2	.95	.90	1.4	.4	2.8	-	-	25	18	4	3.1
11	16	12	17	70	1.1	.95	.80	.65	1.4	.55	1.3	-	-	32	25	19	1.0
12	15.2	13.5	18	61	1.0	.50	.40	.24	2.5	.7	.8	30	500	25	20	16	1.6
13	14.5	15	-	83	1.2	.61	.42	.14	2.9	.4	-	30	540	-	-	-	-
18	22.5	23	25.5	60	.70	.48	.10	-	7	2.0	4.8	10	385	24	22	21	3.2
			mean ±S.D.		.92 ±.20	.52 ±.35	.34 ±.27	.47 ±.34	3.72 ±1.68	1.20 ±.70	3.24 ±2.40	15.4 ±9.0	378 ±80	25.0 ±4.6	19.8 ±4.2	13.0 ±8.0	2.80 ±1.60
			# of meas. (S.D./mean)		(N=12) ±22%	(N=9) ±67%	(N=12) ±79%	(N=11) ±72%	(N=12) ±45%	(N=12)	(N=5)	(N=10)	(N=10)	(N=5)	(N=5)	(N=5)	(N=5)
XHX																	
14	18.5	16	-	54	1.36	.67	.55	.37	2.5	.6	-	24	600	-	-	-	-
15	21	21	26.5	54	1.65	.93	.61	.34	2.7	.4	.9	20	700	18	17	8	1.34
16	24.5	25	26	50	2.4	2.6	1.6	.61	1.5	.8	2.6	12	1160	17.5	17	11	1.75
19	30	24	27	50	.90	.48	.29	.33	3.1	1.2	-	20	405	23	21	10	.76
			mean ±S.D. # of meas.		1.58 ±.63 (N=4)	1.17 ±.97 (N=4)	.76 ±.58 (N=4)	.41 ±.13 (N=4)	2.45 ±0.68 (N=4)	0.75 ±.34 (N-4)	1.75 ±1.20 (N=2)	19.0 ±5.0 (N=4)	716 ±320 (N=4)	19.50 ±3.04 (N=3)	18.33 ±2.31 (N=3)	9.67 ±1.53 (N=3)	1.28 ±.50 (N=3)
			(S.D./mean)		±40%	±83%	±76%	±32%	±28%								
Chieftan 6% Pr.																	
17	24	27	28	75	.95	.82	.57	.37	-	1.2	8.8	15	350	32	28	28	1.28
Fullex																	
20	-1	10.5	-	54	1.1	-	-	-	-	.8	-	-	-	-	-	-	-

TABLE NO. 2

THE VISCOSITY AND SURFACE TENSION OF MIXTURES OF JET-X DETERGENT FOAM CONCENTRATE WITH WATER

% Concentrate (by volume)	Viscosity (centipoises) (at 25°C)	Surface Tension (dyne/cm) (at 21°C)
0	1.00	72.5
1	1.04	46.5
3	1.04	33.3
10	1.11	26.8
30	1.34	24.3
100	3.42	24.2

FIGURE 1. THE FOAM JUST AFTER CREATION IN THE LARGE TEST BOX: COMPARISON OF BLACK BACKGROUND WITH NONE.

The explosive charge was a 2 lb. sphere cast from RDX-TNT (60% and 40 %, respectively) held 8" off the ground above a 3' square steel plate and detonated by electrical initiation of a 2 oz. "shure-shot" booster. Standard DRES gauge stands were used for side-on overpressure and fireball temperature measurements.

The foam was held in place by a 6' high wire mesh fence (of 6" square holes) covered by 2 mil thick polyethylene "vapour barrier" plastic sheeting. The container could be filled with foam in 10 minutes and the charge was detonated about 15 minutes after the start of foam generation.

Pressure measurements from gauge #2 were only done under foam, since at a distance of 3' an off-scale reading could be expected in air.

4. (b) Instrumentation

All pressure and temperature gauges were mounted in standard DRES side-on gauge mounts (Muirhead 1968).

The mounts were 36" high, holding the gauge 30" off the ground with the airfoil shape of the gauge stand causing minimal disturbance of the shock wave.

The temperature gauges were adapted from commercially-available thin film nickel foil resistance temperature probes. The results of those measurements from the same set of explosions reported here were documented by Klautt and Hill (1977).

The pressure gauges used were the piezoelectric type developed at DRES (Muirhead 1967). The pressure gauges used must be linear, reproducible, have a good waveform and show minimum ringing. The first stage in selecting gauges was to test about 40 in a lab-bench air-driven shock tube. The best 15 gauges, judged on linearity, reproducibility and waveform were further tested in field trials with 2 lb. charges. Six of the best gauges were finally selected. Most show appreciable (10-40%) ringing, which depends mainly on the individual gauge, and to a lesser extent on the particular stand used. To reduce ringing, the gauge stands were filled with sand and the gauges were screwed tight using teflon tape wrapped around the threads.

The field measurements also record the electromagnetic pulse, especially at the 3' and 4' distances which are within the fireball. The placing of cables and the use of proper grounding, including grounding the steel plate, help to reduce but not eliminate this pulse, which is usually only short-lived.

The output from the pressure gauges is fed through a signal conditioning amplifier to an Ampex 14-channel tape recorder, as described by Muirhead (1967).

A better pressure gauge for these experiments would be one which could be used closer to the charge. Such a gauge would have a higher overpressure range, be insensitive to temperature and have a faster response with correspondingly less ringing. A prototype for such a gauge has been developed by the University of Calgary (de Krasinski and Ramesh 1976).

4. (c) Calibration Experiments

To avoid blasting holes in the ground, the first 2 lb. charge was set off sitting on the surface of a square steel plate, 3' x 3' x 2". This created a circular hole 1/4" deep and 2-1/2" diameter. Subsequent shots were fired with the charge mounted on top of an expendable 8" high wooden stand.

Initially, the polyethylene sheet supporting the form was held up by a finer metal mesh fence (mesh size 3 wires/in.) which prevented the plastic sheet from breaking. This meant that the bulk of the shock wave impulse was absorbed by the fence, loosening the posts in the ground and resulting in much less transmitted overpressure. Substituting 6" squares for the mesh size, the polyethylene sheet broke and the transmitted pressure wave was within 10% of the value in the absence of plastic. The wooden fence posts supporting the wire mesh have a small effect on the shock wave. Just directly behind a post one sees a small secondary shock peak which may cause ∿ 10% errors in overpressure, impulse, and positive duration at a distance of 3', and less if farther away or not directly behind the post.

In the final layout of gauges, fence, etc., five 2 lb. test shots were fired to produce baseline values for the parameters defining the shock front.

4. (d) Foam Trials

The results from three explosions under foam were measured and compared to the free-air results for the same cnarge and layout. A high-speed photo of an explosion under foam 35 ms after detonation is shown in figure 13. The shock wave is described by the usual parameters of peak overpressure, positive impulse, positive duration, rise time and time of arrival, as defined by Baker (1973). All of these parameters are altered by the foam.

During these preliminary measurements, useful results were obtained from most, but not all, of the pressure transducers used in three foam trials. All data were taken using high-expansion detergent foam concentrate, mixed in 1% concentration with water at 9 ± 1°C temperature. One trial was performed with each of the three brands (XHX, Jet-X and Fullex) yielding very similar results which are displayed together in figures 14-16. The free-air plot is the average of five explosions fired in air under otherwise identical conditions. The distance axis measures the direct distance from the centre of the charge to the centre of the pressure gauge. The peak overpressure outside the foam (fig. 14) is reduced about X20, and the time of arrival of the shock front (fig. 16) is increased X2-3 both inside the foam and outside. The change in measured positive impulse is more complex (fig. 15). First of all, the different impulse at 6' between air and foam measurements is misleading because the 6' gauge in air really measures the explosion through 5' of foam and 1' of air. The free-air impulse curve reaches zero slope at 6.5', the size of the visible fireball. The foam curve is relatively flat from 3'-4' which may indicate that the fireball effective diameter under foam is reduced to 3'-4'.

The foam rounds off the shock front so that the rise time to maximum overpressure is changed from microseconds to about .2 ms at 3', .7 ± .2 ms (4'),

1.6 ± .3 ms (6') and 2 ± .2 ms (9'). The positive duration is inherently more difficult to measure, and is of no direct importance for damage to structures, so no graph has been plotted. The data indicate that it is increased by a factor of about 3-5 over the 4'-9' range.

4. (e) Discussion of Results

As the charge is off the ground, there will be a Mach stem formed, and the path of the triple point relative to the gauge positions should be calculated. The result, from figure 5.23 of Baker (1973) shows that for 2 lb. of TNT centred 10" off medium ground, the stem height of 30" (scaled to the charge weight using $2^{1/3} = 1.26$) is attained at a distance of 53" or 4'4". This means that the gauges at 3' and 4' do not measure the Mach stem overpressure while all others do. This problem should be investigated, including the motion of the presumed Mach stem and triple point under foam.

The two parameters pertinent to structural damage are peak overpressure and positive impulse. Since these are short duration pressure waves the impulse figure is more relevant to material damage.

Unfortunately, it was not possible from these experiments to relate foam physical properties to the blast attenuation properties.

A simple calculation indicates that the foam contains enough water to absorb the explosion energy entirely by vapourization of water. The heat of the explosion is given by Cook (1958) to be about 1125 cal/g for TNT. The energy to vapourize water at room temperature, which is the latent heat of vapourization plus 80 cal/g to heat the water to the boiling point, is 620 cal/g. If all the heat of explosion goes 100% into vapourizing water, then 1 g of TNT vapourizes about 2 g of water, or 1 lb. of TNT per 2 lb. of water. Since the density of high-expansion fire-fighting foam is $\gtrsim .3$ lb./ft.^{3}, the radius of a hemisphere of foam, with all water completely vapourized, would be $r \doteq 1.5\ W^{1/3}$ ft. where W is the charge weight in lb. TNT. Since the radius of an undisturbed hemispherical TNT fireball is given by $r \doteq 6\ W^{1/3}$ ft., it is apparent that there is sufficient water within the nominal fireball volume to remove the entire heat of explosion. Even allowing for a rate of heat transfer from

fireball to water which is only 2% efficient, there would be enough water in a 6 ft. radius hemisphere to absorb all the energy of 1 lb. of TNT.

5. SUGGESTIONS FOR FURTHER RESEARCH

The following suggestions are made for further basic experimental and theoretical research in this area:

1. Develop sets of data on how each of the blast reduction properties depends on charge weight, depth of foam and all the foam physical properties.

2. Arrange for industrial assistance in the creation of new foams and in the use of established standard methods for measuring such properties as foam drainage and shear strength.

3. As the effect may be due largely to the action of the foam water on the fireball, compare foams of various densities with just water surrounding the charge.

4. Try to measure the total energy yield of the explosion by more fireball temperature measurements and/or other techniques.

5. The RDX-TNT mixture used is approximately balanced for O_2 content (Cook 1958). The effect of other explosives with an oxygen deficit or excess would also be of interest. If the foam were made with N_2 gas that would help extinguish possible afterburning.

6. To separate the effect of foam on the shock wave from the effect on the fireball, one should do shock tube measurements. This would also involve the simpler one-dimensional geometry.

7. Study the results of shock tube experiments with shaving foam, as reported by Prof. J.S. de Krasinski of the University of Calgary, and his co-workers Khosla, Ramesh and Anson (see list of papers). They found that a shock front reflected back through the disturbed foam suffered strong attenuation on the return path.

The following suggestions are offered for the theoretical development:

1. Develop empirical scaling laws for one well-defined foam as a function of charge weight (or shock strength in the shock tube) and foam depth. It should be possible to relate the scaling law for the one-dimensional geometry of the shock tube to the three-dimensional geometry of explosions under foam. For the latter this would only apply to shock attenuation outside the fireball.

2. Consider expressing the results theoretically in terms of the coordinate system developed by Khosla (1974). It separates, to some extent, the effects of dispersion and attenuation.

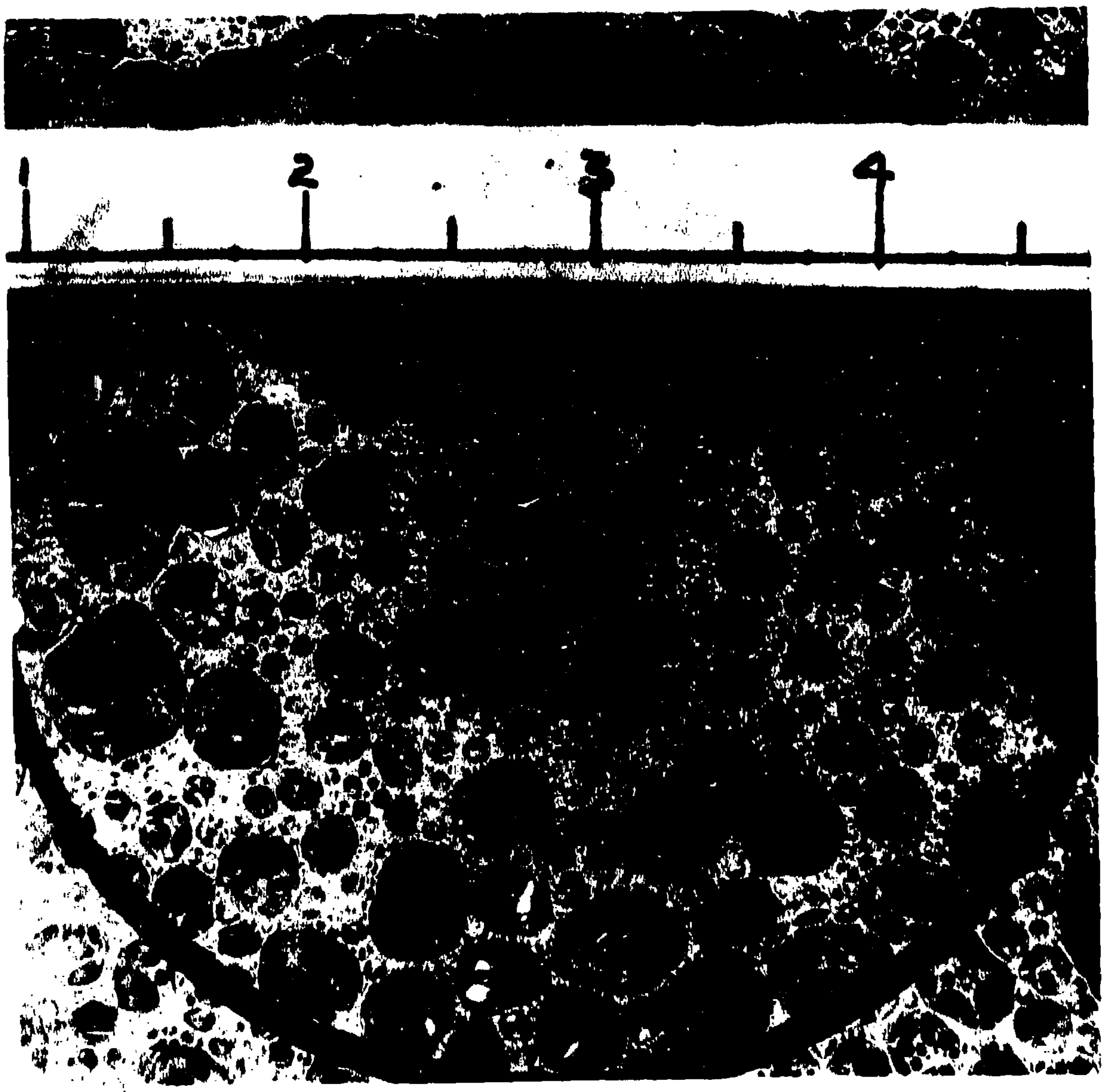


FIGURE 2. CLOSE-UP OF DETERGENT FOAM INSIDE A 4" CIRCLE.

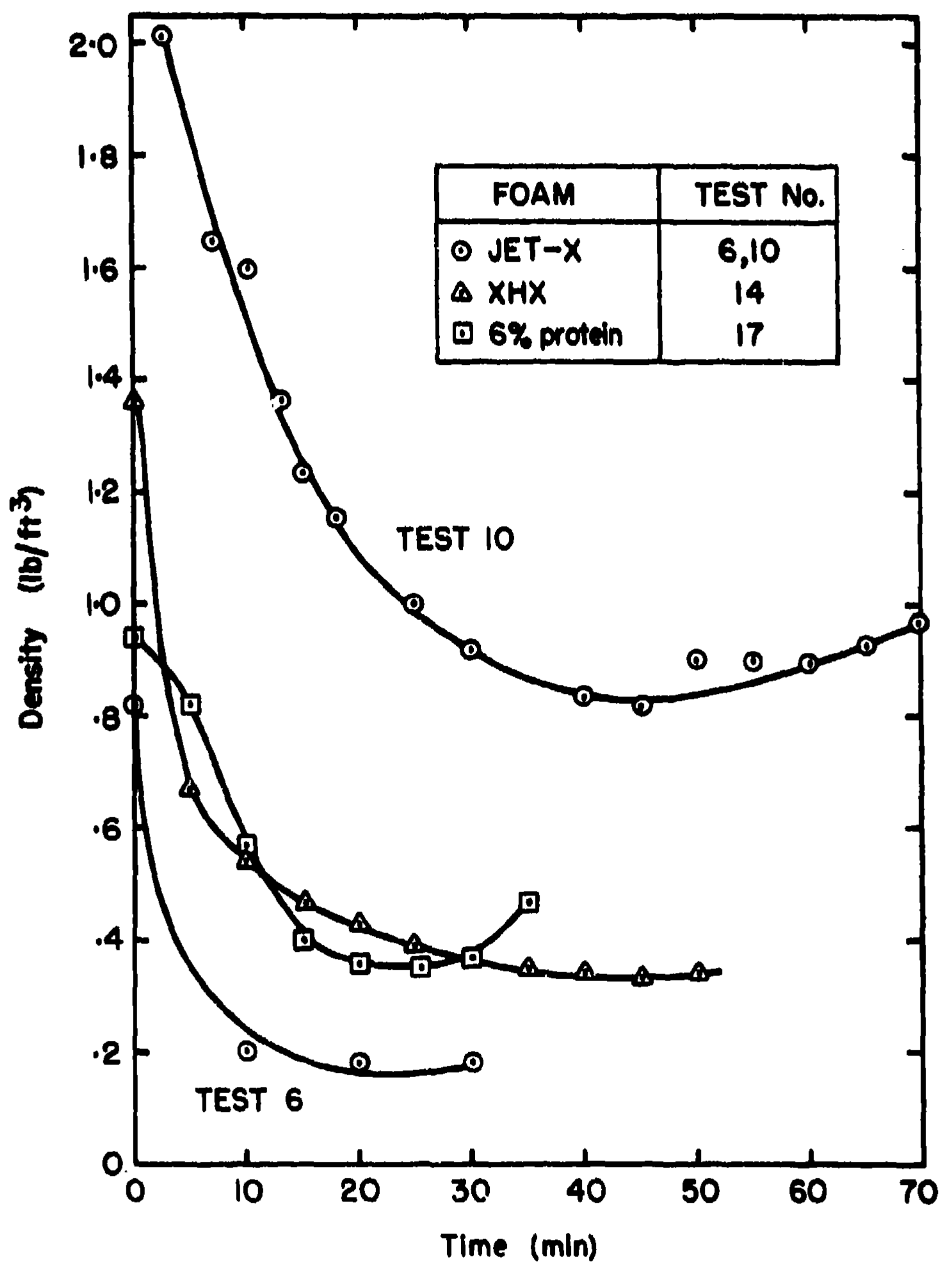


FIGURE 3. TYPICAL DENSITY-TIME DATA.

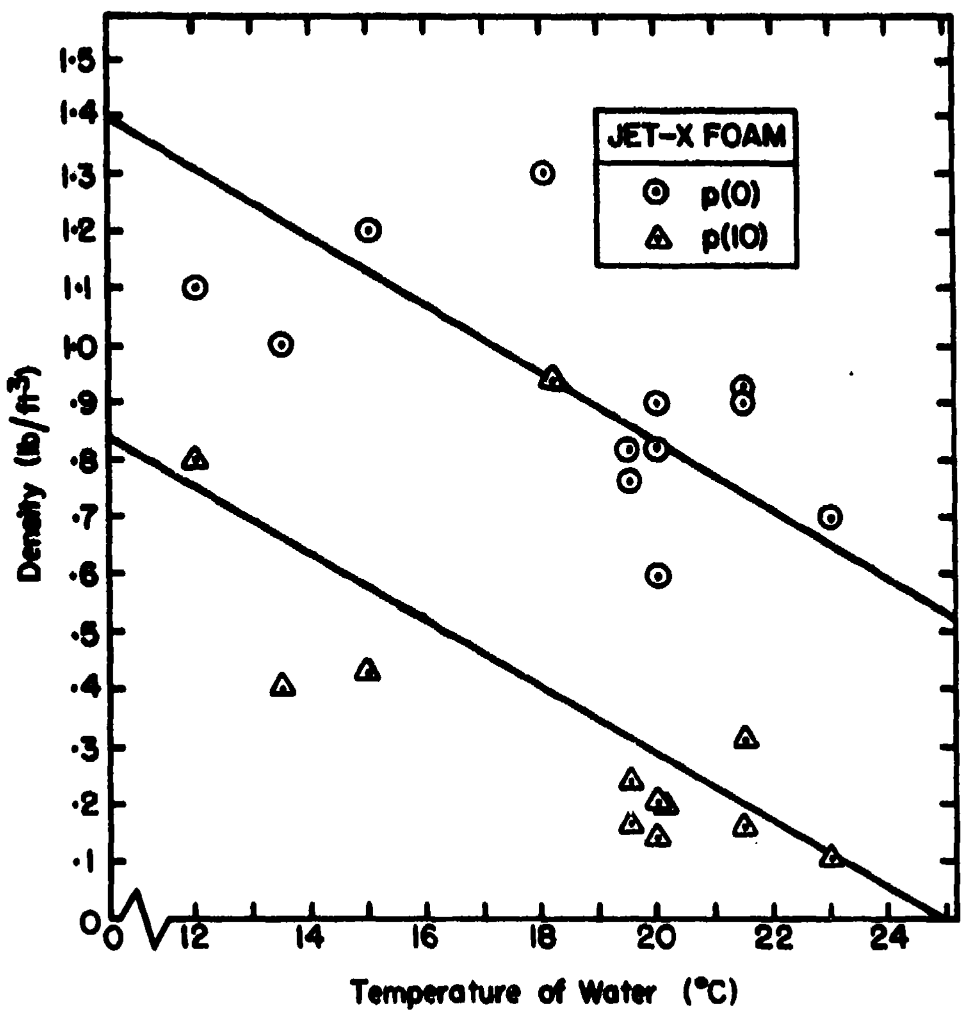


FIGURE 4. THE DEPENDENCE OF FOAM DENSITY ON WATER TEMPERATURE FOR JET-X FOAM.

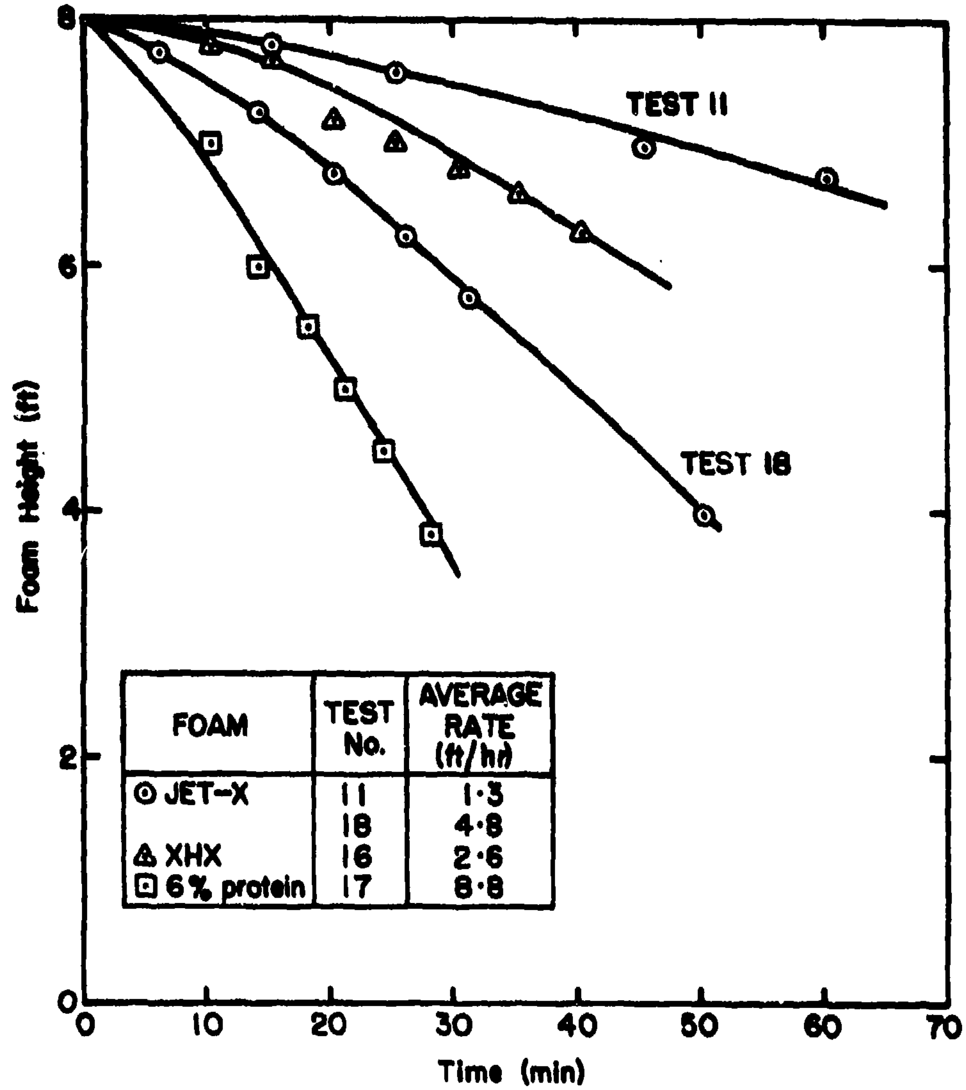


FIGURE 5. THE RATE OF FOAM SUBSIDENCE IN THE LARGE BOX.

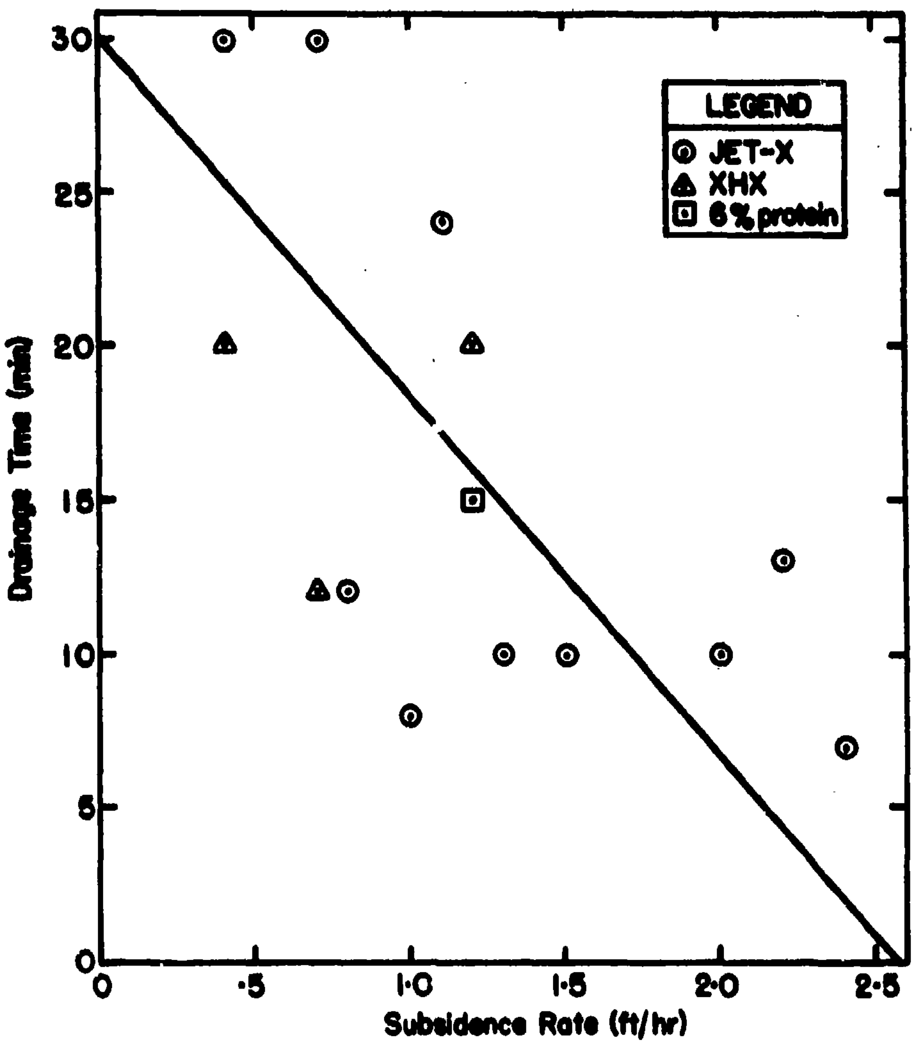


FIGURE 6. THE RELATIONSHIP BETWEEN DRAINAGE RATE AND SUBSIDENCE RATE IN THE LARGE BOX.

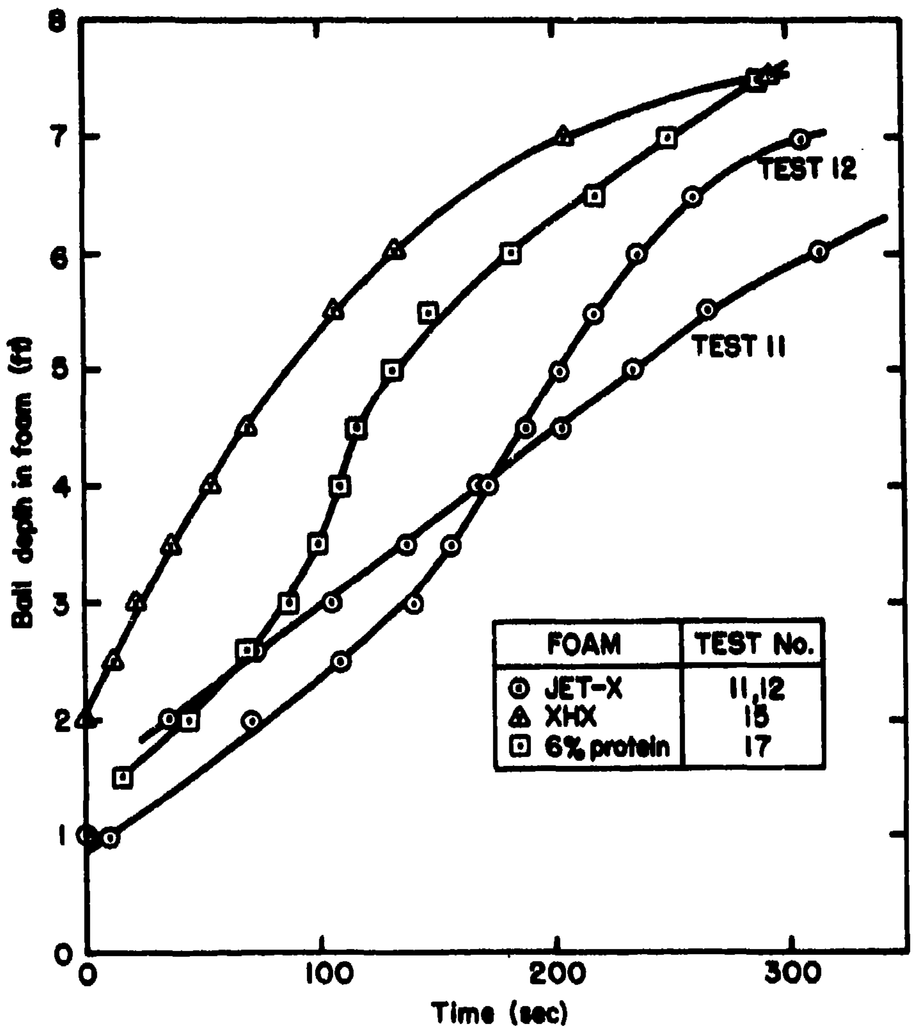


FIGURE 7. TYPICAL CURVES FOR THE BALL PENETRATION RATE.

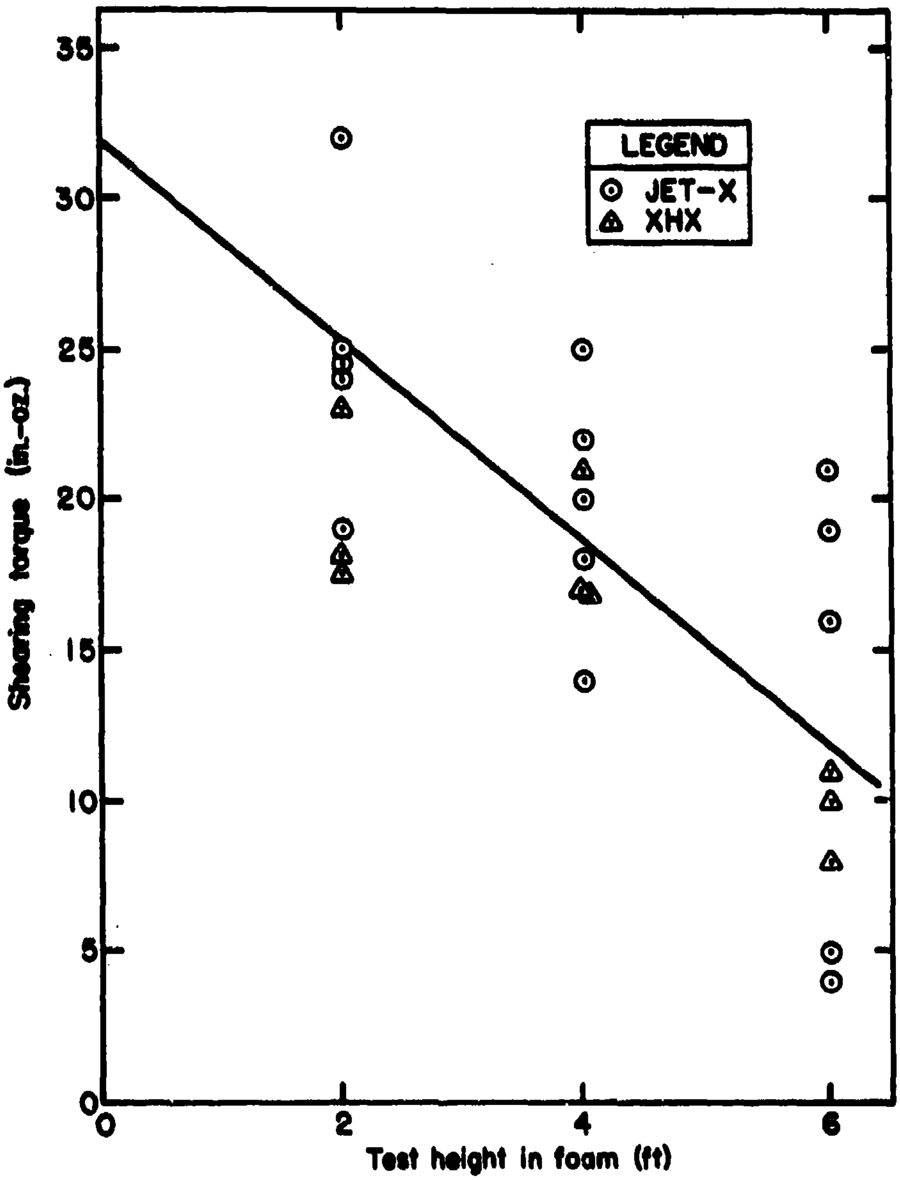


FIGURE 8. THE DEPTH DEPENDENCE OF THE SHEAR STRENGTH.

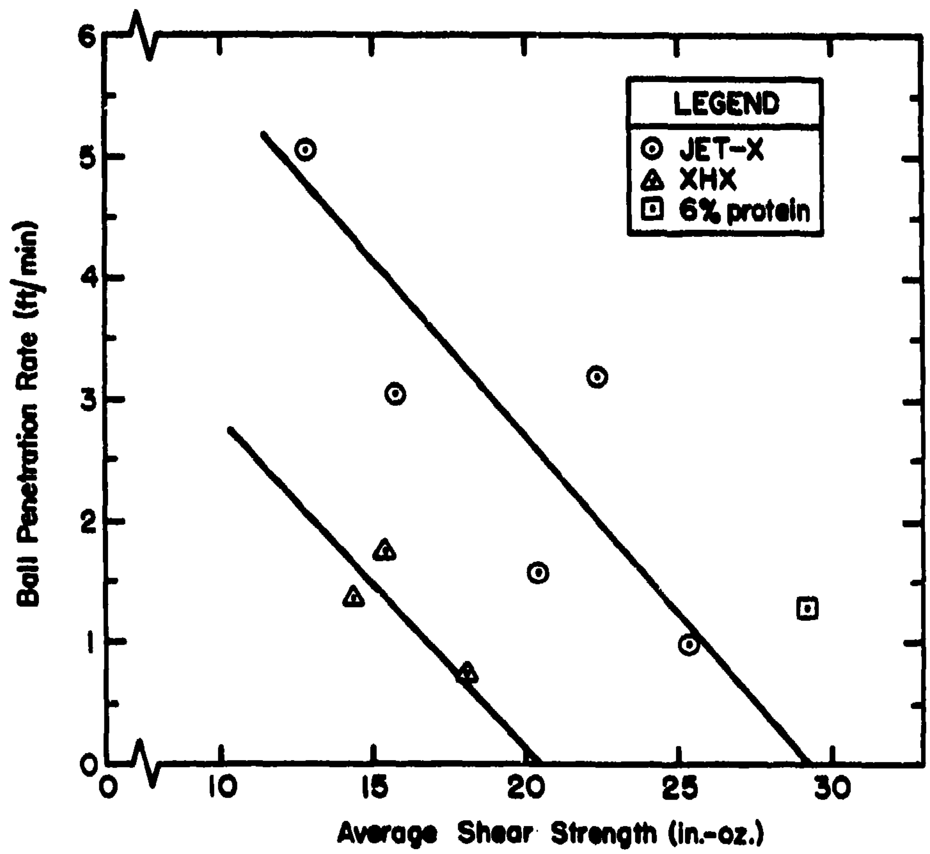


FIGURE 9. ILLUSTRATION THAT BALL PENETRATION RATE AND SHEAR STRENGTH BOTH MEASURE FOAM STIFFNESS.

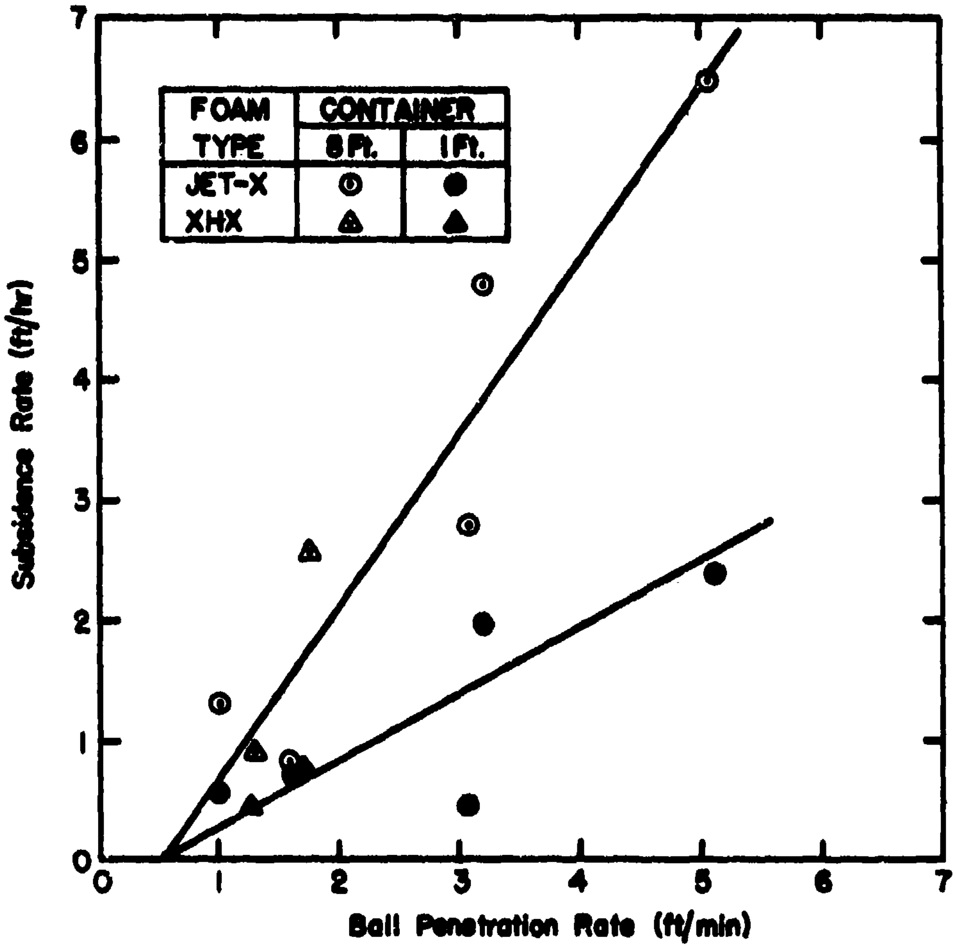


FIGURE 10. THE RELATIONSHIP BETWEEN SUBSIDENCE RATE AND BALL PENETRATION RATE.

FIGURE 11. (A) LAYOUT OF EXPLOSIVE CHARGE, GAUGE STANDS AND WIRE/PLASTIC FOAM SUPPORTING FENCE.

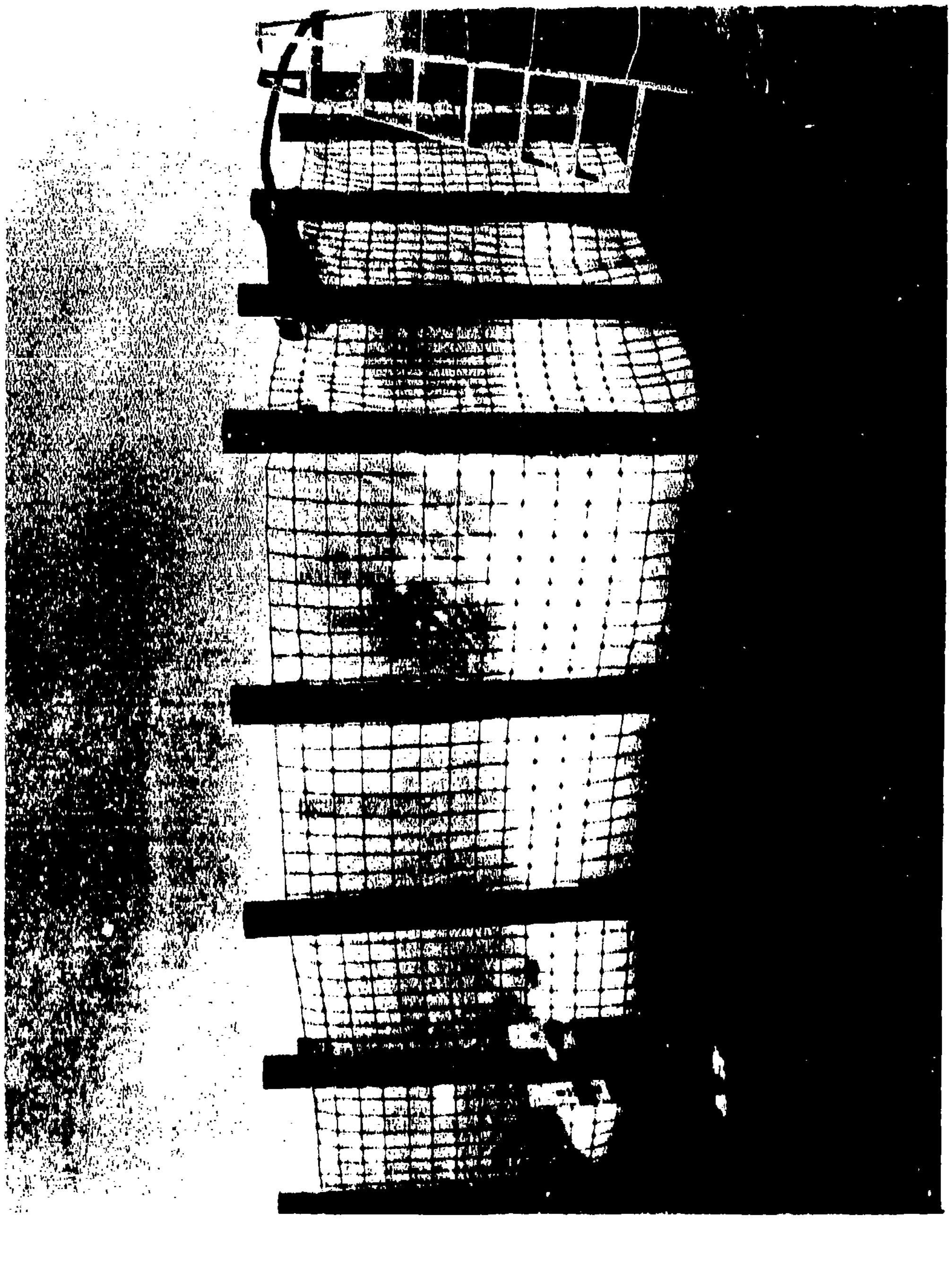
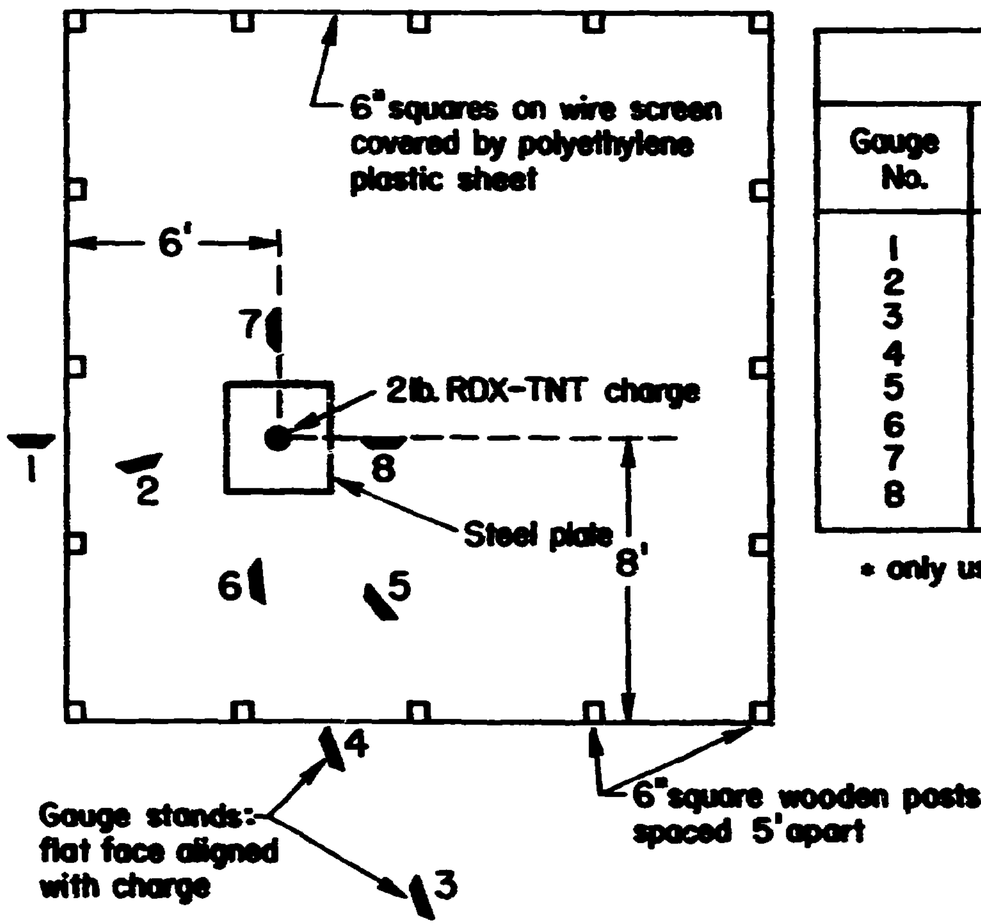


FIGURE 11. (B) FILLING THE APPARATUS WITH FOAM.



LEGEND		
Gauge No.	Distance (Ft.)	Pressure/ Temperature
1	6	P
2	3	P*
3	14	P
4	9	P
5	6	P
6	4	P
7	3	T
8	4	T

* only used under foam

FIGURE 12. LAYOUT OF PRESSURE AND TEMPERATURE GAUGES FOR EXPLOSIONS UNDER FOAM.

FIGURE 13. HIGH SPEED PHOTOGRAPH OF AN EXPLOSION UNDER FOAM.

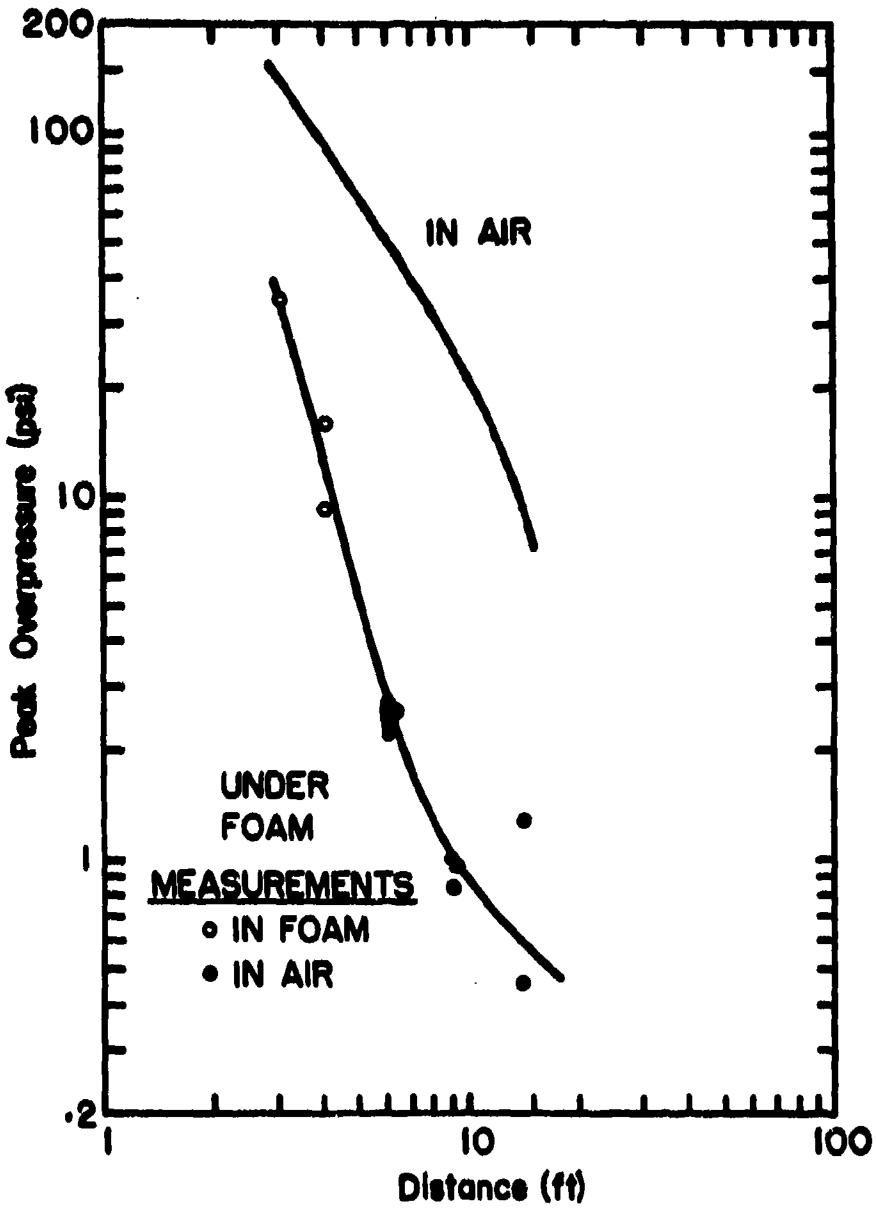


FIGURE 14. PEAK OVERPRESSURE REDUCTION UNDER FOAM.

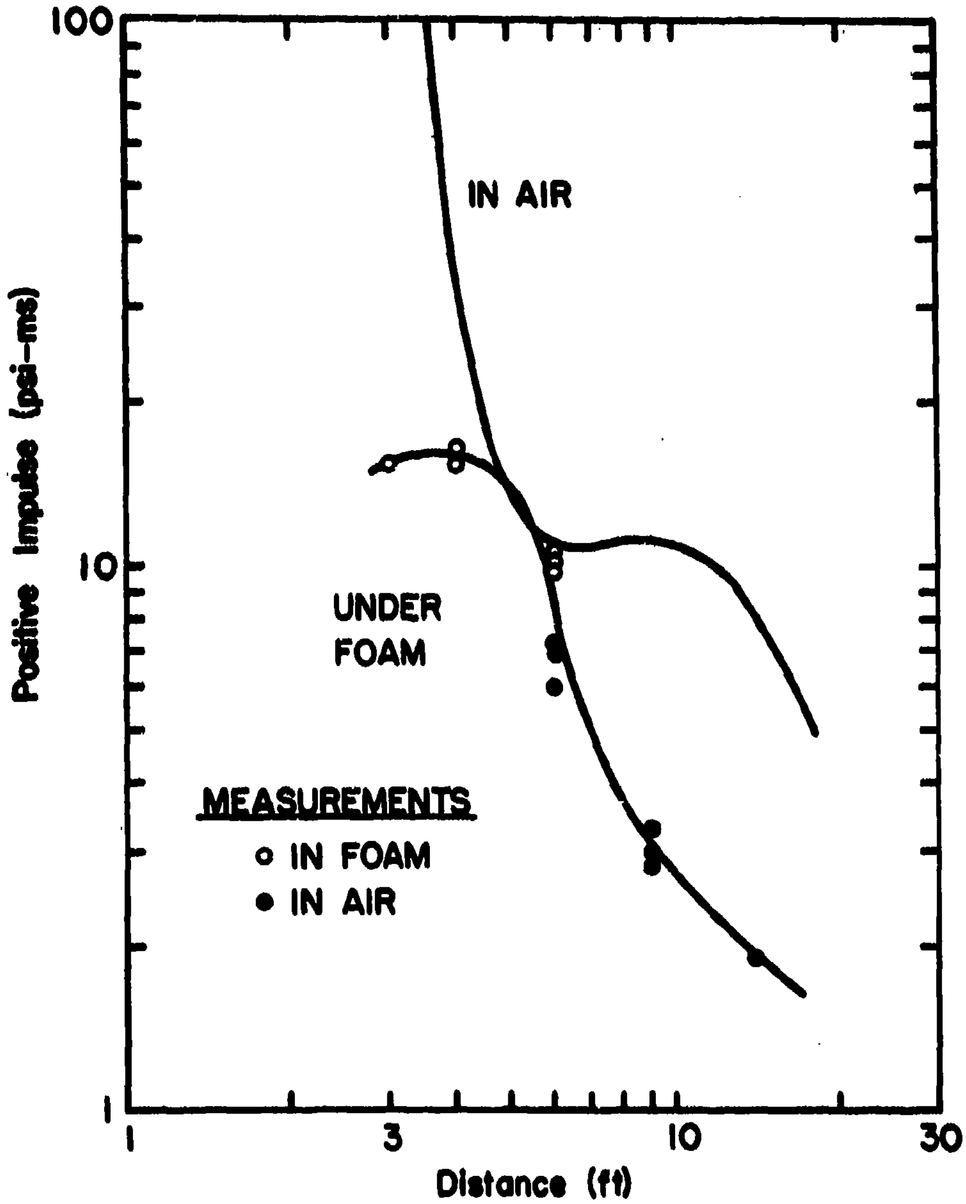


FIGURE 15. POSITIVE IMPU_SE REDUCTION UNDER FOAM.

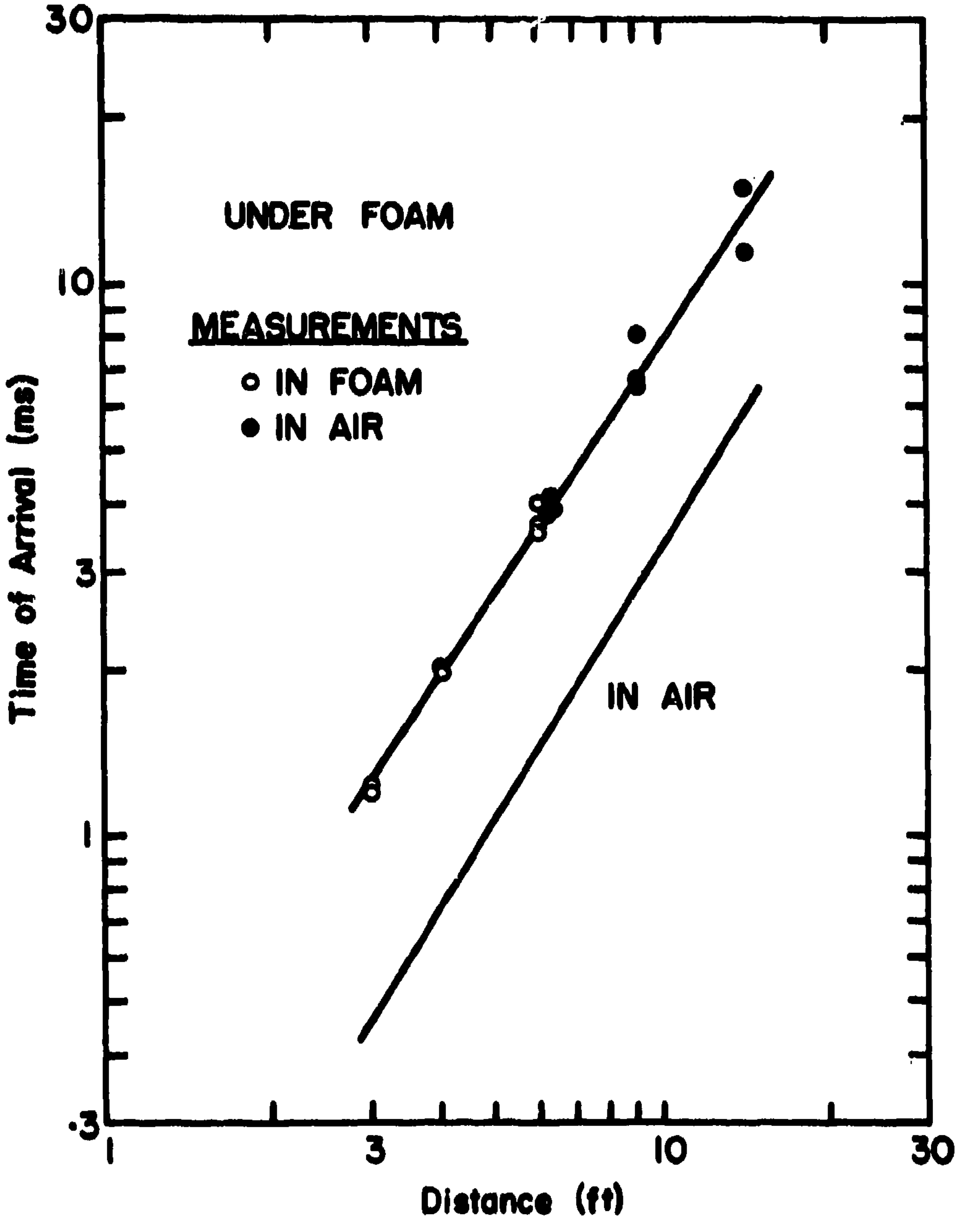


FIGURE 16. TIME-OF-ARRIVAL INCREASE UNDER FOAM.

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Preliminary results are presented from experiments designed to correlate the physical properties of aqueous foams with their blast attenuation characteristics. Using commercial concentrates for detergent based (high expansion) foams, the physical properties of density ($\sim .4 \pm .2$ lb./ft^3), subsidence rate ($\sim$ 2-5 ft./hr.), drainage time (10-25 min.), ball penetration rate (1-4 ft./min.) and shearing torque (10-25 in.-oz.) were measured. The shock front in foam showed a decrease in the damage-producing properties of peak overpressure (reduced X20) and positive impulse (reduced X4). An increase was recorded in shock front time of arrival (X2-3), rise time ($\sim$ 1 ms. vs 1 μs.) and positive duration (X3). The project was terminated before the correlation between physical and blast attenuation properties could be studied.

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KEY WORDS

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blast attenuation
test methods

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